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Numerical simulation of migration behavior of uranium ore dust particles in the human respiratory tract

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Abstract. There is a certain concentration of radioactive dust particles in the air of workplace of underground uranium mines. Some small diameter particles will pass through the masks and enter the respiratory tract which will cause radiation damage to the human body. In order to study deposition regularity of uranium dust in the human respiratory tract, in this paper, we firstly use the RNG turbulence model to simulate the gas flow field in the human respiratory tract $Z_0 \sim Z_3$ level under different respiratory intensity. Then we use DPM discrete phase model to simulate the concentration, particle size distribution, deposition rate and deposition share of uranium dust particles after being filtered through the masks in the human respiratory tract Z_0 to Z_3 bronchus. According to the simulation results, we have got the following conclusions: the particles' number concentration of uranium dust after being filtered through the mask in the human respiratory tract basically decreases with the increasing of particle size under different respiratory intensities on the environment of uranium mine. In addition, the intensity of respiration and the mass concentration of particles have an important influence on the deposition rate and the deposition of particles in the respiratory tract.

1. Introduction

Mine dust comes from mining blasting, drilling and transporting activities under the pit. There are a lot of radioactive nuclides such as radium, uranium, radon daughters and so on. If these radioactive aerosols go into the human body through breathing, the human body would suffer internal radiation damage, which greatly endangers body health. Studies have indicated that particulate matter of aerodynamic equivalent diameter less than 10 microns (PM10) can be directly inhaled into the upper respiratory tract. Aerodynamic equivalent diameter less than 2.5 microns fine particulate matter (PM2.5) can enter the alveolar. The pollution of fine particulate matter is closely related to the health effects of respiration and the occurrence of cardiovascular diseases [1,2], when the concentration of PM2.5 was increased by $10 \mu\text{g}/\text{m}^3$, the incidence of total morbidity, cardiovascular disease and respiratory disease increased by 4%, 6% and 8%, respectively [3-5]. With the decrease of the particle size, the toxicity increased [6].

With the rapid development of computer technology, computational fluid dynamics CFD technology has obtained the wide use. CFD numerical simulation technology has the advantages of fastness, accurateness and low cost. It can simulate many experiments in more complex conditions. It broadens the scope of experiment research greatly. Many scholars at home and abroad have applied the CFD technology into the particle simulation experiment of respiratory tract. Cheng et al. [7-9],



according to the human true respiratory tract size, established a three-dimensional model of the upper respiratory tract and carried out the relevant experimental study. Zhang et al.[10] pointed that Weibel established a symmetrical three level bronchial model A and later many scholars have used this model to carry out a large number of numerical simulation studies. Luo and Liu [11] used the LRN κ - ϵ model to simulate the traffic status of the particles in the human respiratory tract, studied the influence of stokes number and Reynolds on deposition rate and deposition distribution in the respiratory tract. Although there are a number of examples about the scholars using CFD to simulate the particle movement of respiratory tract, the simulation study about the uranium mine radioactive aerosol particles in the respiratory tract has not been reported widely. Therefore, we used the CFD numerical simulation technology to simulate uranium ore dust particles size distribution and deposition rate in the different positions of human respiratory tract in different respiratory intensities after being filtered through the mask, and investigated the causes of particle concentration, particle size distribution, deposition rate distribution and deposition ratio in human respiratory tract. As a result, it will provide some referential information for preventing the diseases of respiratory tract.

2. Numerical models and method

2.1. Respiratory geometric model size

The depth that particles in different sizes go into the human respiratory system is different. Generally, particles whose size is 5 to 10 μm can be removed by a physical mechanism in the throat. Particles whose size is less than 5 μm can get through the block of the throat and go into the human bronchus. Particles whose size is less than 2.5 μm will go into the deepest part of the lungs with respiratory airflow [12]. Contrasted with previous studies, the mass concentration of uranium dust distribute in less than 3 μm size range after filtering through the mask. These tiny particles easily go through the mouth, nose and throat to human bronchial and alveolar. For this reason, this paper uses the Weibel three-dimensional bronchial model that does not include the human nose and throat to research on particulate deposition situation in Z_0 to Z_3 bronchial [13]. The bronchial tubes are connected by a circular tube. The respiratory model and its partition are shown in figure 1. The length, diameter and curvature of the bronchial tubes at all levels are shown in table 1.

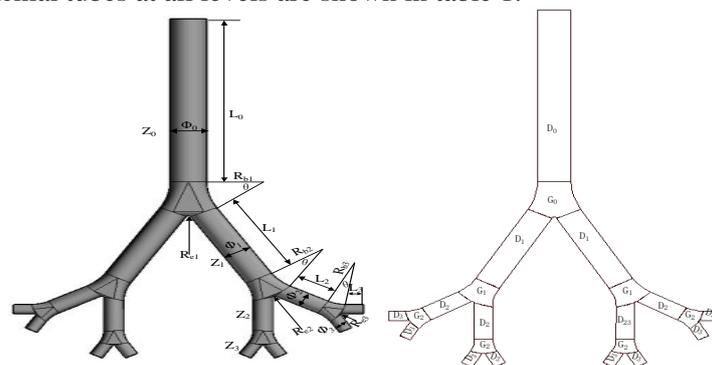


Figure 1. Weibel three-dimensional bronchial model A and partition number
Table 1. Geometric parameters of Weibel three-dimensional bronchial model A .

Tracheal bronchus	Diameter D(mm)	Length L(mm)	Radius of curvature of bronchus R_{bi} (mm)	Radius of curvature of carina R_{ei} (mm)	Bronchial semiangle θ°
Z_0	$\Phi_0=15.4$	$L_0=102.6$	—	—	30
Z_1	$\Phi_1=12.2$	$L_1=47.6$	$R_{b1}=32.94$	$R_{e1}=1.22$	30
Z_2	$\Phi_2=8.30$	$L_2=19.0$	$R_{b2}=22.41$	$R_{e2}=0.83$	30
Z_3	$\Phi_3=5.60$	$L_3=7.6$	$R_{b3}=15.12$	$R_{e3}=0.56$	30

2.2. Before the simulation data acquisition

We place the APS 3321 in planned sampling position and connect backup battery power and notebook computers to make them in the ready state. The mask is put in the APS 3321 air inlet and open the switch for pumping, We observe the data of APS 3321 and wait for the concentration of quality is stable or not occur significant fluctuations. We start sampling for 300 seconds and write the data into computer. The above test is repeated at each sampling point. The monitoring data of APS particle size spectra instrument are put into ORIGIN software for processing. We have got the particle size distribution of uranium dust after being filtered through the mask. As shown in figure 2.

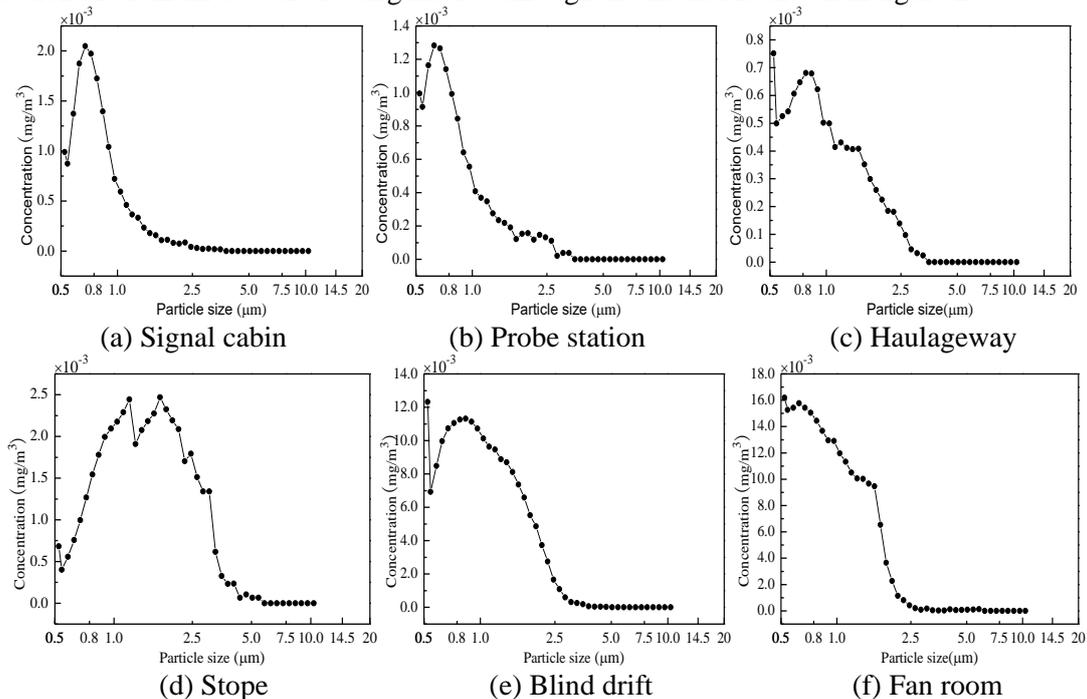


Figure 2. The particle size distribution of uranium dust after being filtered through the mask.

The body's respiratory rate approximate a sine curve. The human body respiration intensity are 30 L/min, 60 L/min and 90 L/min respectively in the process of mild, moderate and high intensity exercise[14]. In this paper, the respiratory intensity is 30 L/min, 60 L/min and 90 L/min by using RNG turbulence model. The flow field distribution in the human respiratory tract was studied under different labor intensity. The mass concentration of PM10 is taken in simulation. The mass flow rate of uranium dust with respiration into the human body is calculated by combining the respiration rate of human body in mild, moderate and high intensity labor. The results are shown in table 2.

Table 2. Mass flow rate of uranium dust in human respiratory tract under different respiration intensity (kg/s).

	Place	respiration intensity (L/min)		
		30	60	90
Gauze mask	Signal cabin	8.50E-12	1.70E-11	2.56E-11
	Probe station	6.50E-12	1.30E-11	1.95E-11
	Haulageway	1.30E-11	2.60E-11	3.90E-10
	Stope	5.20E-11	1.04E-10	1.56E-10
	Blind drift	9.30E-11	1.86E-10	2.80E-10
	Fan room	4.80E-11	9.60E-11	1.44E-10

Uranium dust being filtered through the mask is distributed in less than 5 μ m diameter particle size range. The particle size distribution can be expressed by Rosin-Rammler distribution function. The R-R

distribution equation of uranium mineral dust is obtained by statistical calculation of the experimental data of uranium mine dust filtered by masks. The results are shown in table 3.

Table 3. Uranium dust R - R distribution table after filtered by the masks.

	Place	\bar{d} (μm)	n	R-square
Gauze mask	Signal cabin	0.880	4.695	0.995
	Probe station	1.139	2.320	0.987
	Haulageway	2.333	1.602	0.989
	Stope	1.729	2.142	0.996
	Blind drift	1.172	2.425	0.993
	Fan room	1.248	2.589	0.995

3. Results and discussion

3.1. The distribution characteristics of the flow field

The flow characteristics of airflow in the respiratory system are closely related to uranium dust deposition in human respiratory system. Therefore, this paper uses RNG turbulence model to simulate the flow field distribution cloud images in the respiratory tract. The results are shown in figure 3.

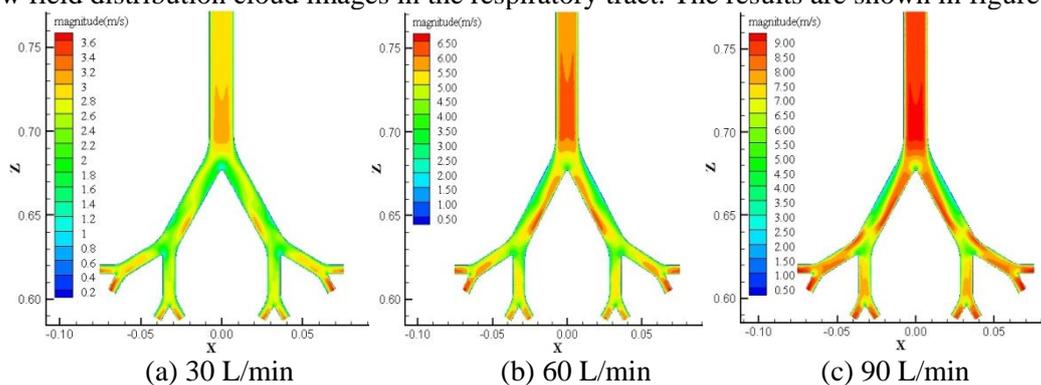


Figure 3. Flow field distribution cloud images under different respiratory intensity in human respiratory tract.

It can be seen from the figure 3 that the airway wall has obvious viscous effects to air, so the air velocity exhibits an obvious parabola distribution. The intermediate speed is larger than the two sides. Air flow produces a small range of reflux at the bottom of the G_0 , G_1 , G_2 section. High velocity fluid is distributed in the inner side of the center line of the D_1 section. The lateral fluid velocity is relatively low. The D_1 and D_2 sections are further reduced. Air does not appear significant high or low speed separation phenomenon.

3.2. Concentration and particle size distribution

In this paper, we simulate the mass concentration and particle size distribution of uranium dust under the respiratory intensity of 30 L/min, 60 L/min and 90 L/min in the human respiratory system. For the various experimental results, we take the results in signal cabin as an example and display the concentration distribution of uranium dust in the human body. As is shown in figure 4.

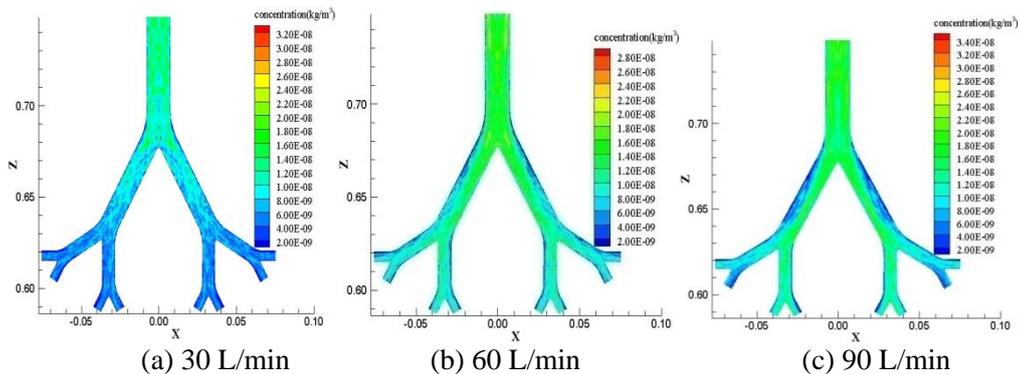


Figure 4. Mass concentration distribution of uranium dust on $Y=0$ cross section.

It can be seen from the figure 4, uranium dust concentration is higher where air velocity is high. Due to the particle's motion trajectory is mainly affected by the impact of air and its trajectory is similar to the trajectories of fluid. When the flow of high-speed airflow is in the respiratory tract, it will take a large number of particles.

3.3. The deposition rate of uranium dust particles in the respiratory tract

In this paper, we have simulated the deposition rate of uranium dust mine after filtering through the mask in different respiratory intensity. Deposition rate distribution diagram of uranium dust in the human respiratory tract is obtained. Because there is a lot of data, we will display the data of signal cabin, as is shown in figure 5.

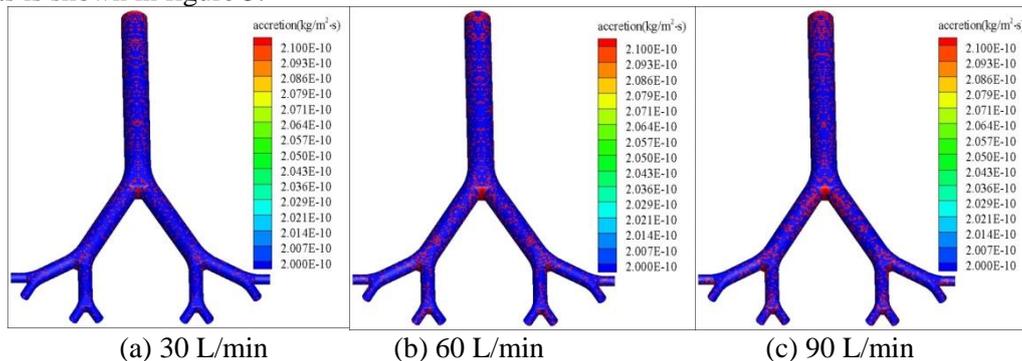


Figure 5. Uranium dust deposition rate in the human respiratory tract.

Through the analysis of figure 5, the deposition rate is bigger in D_0 entrance position where uranium dust concentration is higher. With the continuous adsorption of respiratory tract mucous membrane to uranium dust, the deeper is, the lower uranium dust concentration of the respiratory tract is, the lower the particle deposition rate on respiratory tract mucous membrane is. Therefore, mass concentration is an important influential factor of particle deposition rate in the respiratory tract.

The deposition rate is an important parameter of movement to study particle movement in the human upper respiratory tract. Therefore, airway wall is divided in detail on the basis of figure 1 in this article. The deposition rate is counted in the corresponding region. The deposition rate curve of uranium dust is obtained in Weibel 3D bronchial mode under the different respiratory intensity in uranium underground environment after filtering through the mask, As is shown in figure 6.

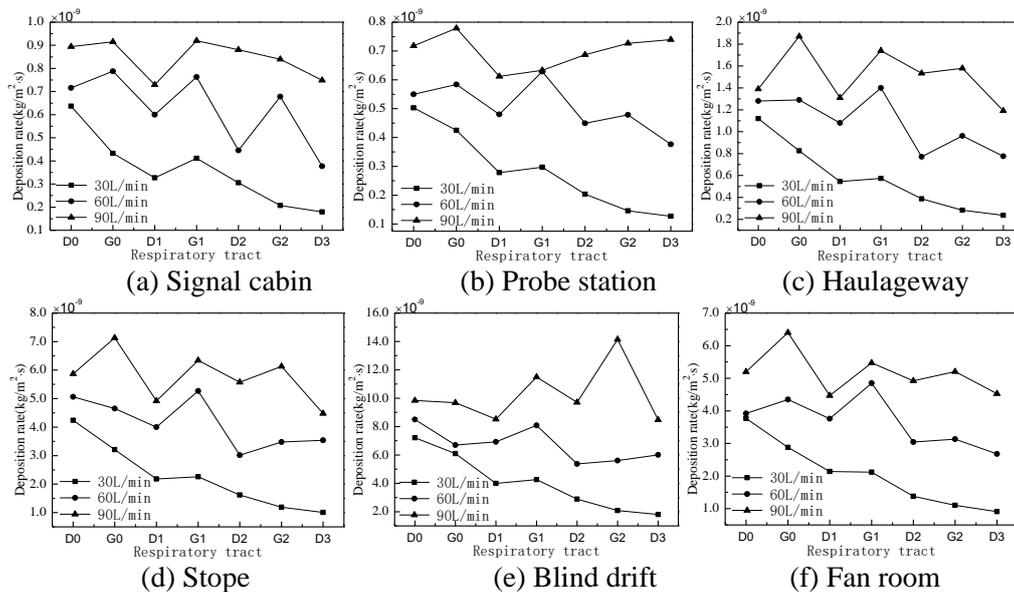


Figure 6. Deposition rate of uranium dust after being filtered through the mask in the human respiratory tract

It can be seen that uranium dust deposition rate was significantly higher than the surrounding straight pipe section in bifurcation segment G_1 from figure 6, due to airway narrowed sharply, airflow that coerced particle impact the bottom of bifurcation section. A large number of particles were adhered to the airway mucosa under the effect of inertia collision. Therefore, the inertia impact is one of the main factors affecting of the particles' deposition rate in the cross section of the respiratory tract. In addition, through the analysis of deposition rate data under the three kinds of different respiratory intensity (mild, moderate and severe), it was found that the deposition rate of particles in respiratory tract increases with the increase of respiration intensity. This is because when the intensity of respiration tract increased, the particle mass increased in the respiratory tract of the human body within the unit time. Therefore, the rate of respiration is one of the main factors affecting the particles' deposition rate in the cross section of the respiratory tract.

4. Conclusions

In this study, the particle number concentration of uranium dust after being filtered through the mask in human body $Z_0 \sim Z_3$ respiratory tract basically decreases with the increasing of particle size under the different respiratory intensity on the environment of uranium mine. Particle number is mainly distributed in the small size range. The smaller the particle is, the deeper the human respiratory system goes, which is consistent with the results of this study.

Through the analysis of the deposition rate data of light, medium and heavy three kinds of respiration intensity, the quality of the particles concentration, inertia collision and the rate of respiration are the key factors affecting of the particles' deposition rate in the respiratory tract. Pathogenesis and treatment of respiratory diseases has a great relationship with the deposition rate of uranium dust in the mucous membrane of the respiratory tract. Through the study of deposition rate distribution of uranium ore dust in respiratory tract, it will help to locate the most serious and most easily diseased parts.

There is a relationship between the deposition share of uranium dust in the human body $Z_0 \sim Z_3$ bronchus and the respiration intensity of the human body. The greater the respiratory intensity of the human body is and the greater the respiratory rate is, the smaller the particle deposition become in the human body $Z_0 \sim Z_3$ bronchus under the same conditions. As the air velocity increases, the residence time of particles becomes shorter in respiratory tract, the probability of entering the deep respiratory tract increases.

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